Intelligent Extruder for Polymer Compounding

GE Industrial Systems Solutions

GE Global Research Center

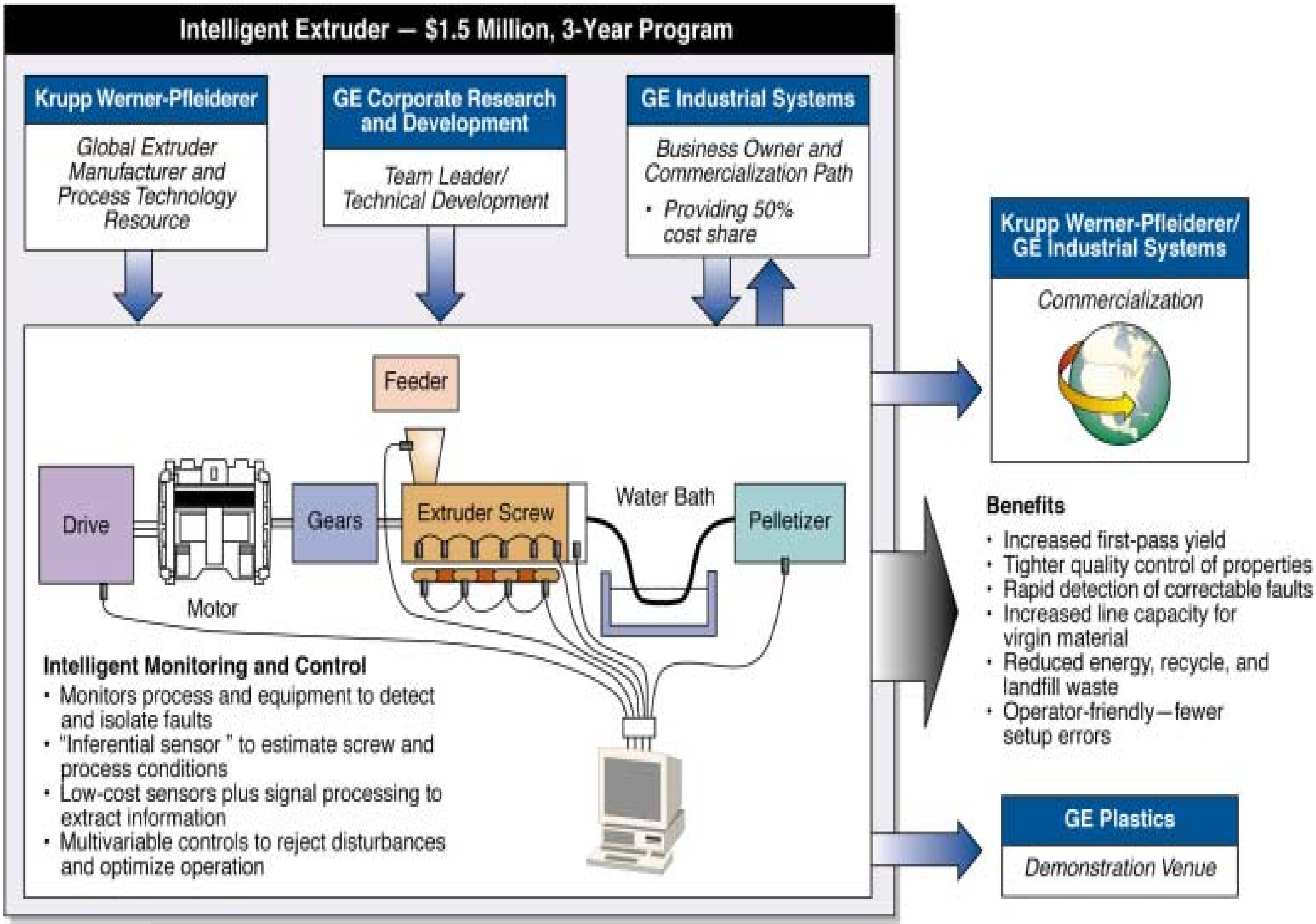
Coperian Werner-Pfleiderer Corporation USA

US Department of Energy / OIT

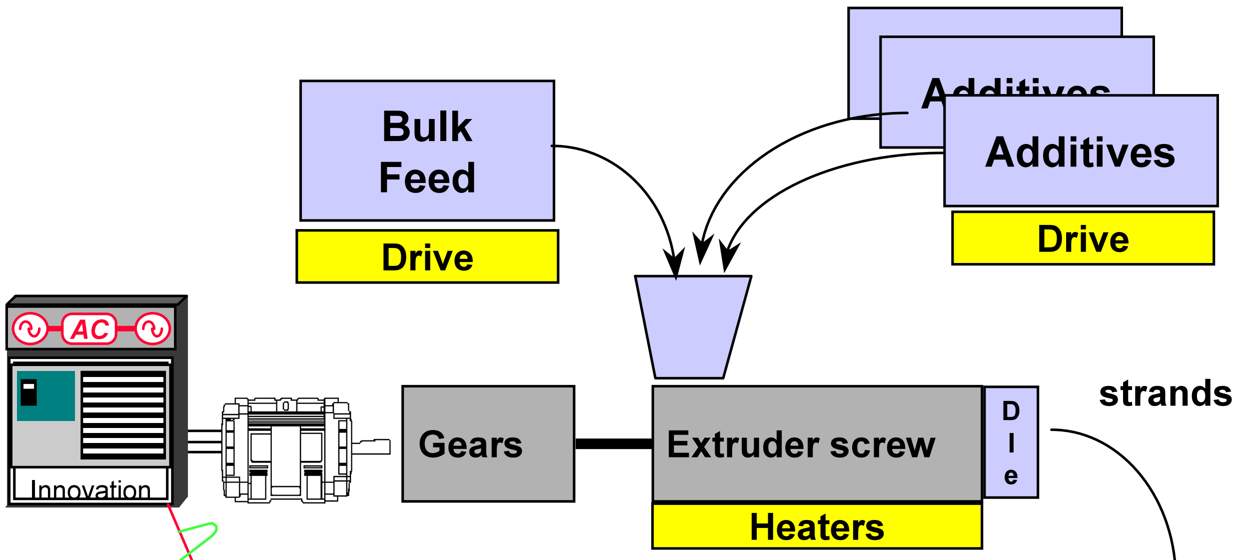
... comments in this font and post-it note color are added to stress key findings for the review committee...

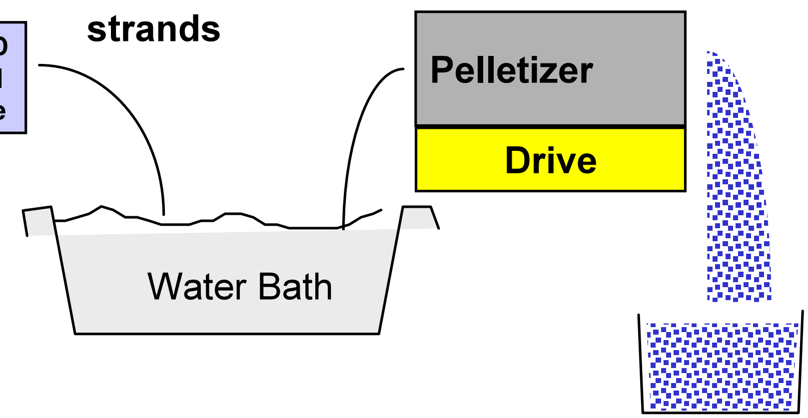
Quality material the first time, every time

GE / Werner-Pfleiderer/ DOE Program Overview



Intelligent Extruder - Objectives





Detect process upsets
- *feeder mat'l flow*
- *feed property shifts*
- *out of spec production*
- *use existing sensors & drive signals*

Estimate key variables
- *material properties (viscosity)*
- *intra batch quality*

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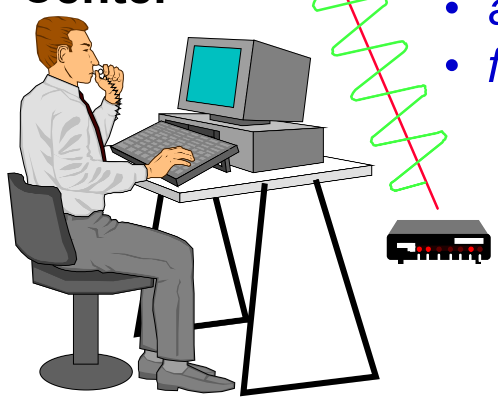


Feedback Control
- *auto fine corrections (MV, comp)*
- *fast changeover (grade)*

Remote on-line support
- *calibration, setup, maintenance*
- *data interpretation, problem solving*
- *24X7 process expertise availability*

Customer Payoff
- *First Pass Yield*
- *'free' capacity*
- *Reduce QA lab testing*
- *less customer returns*
- *reduced landfill waste*
- *lower energy use*

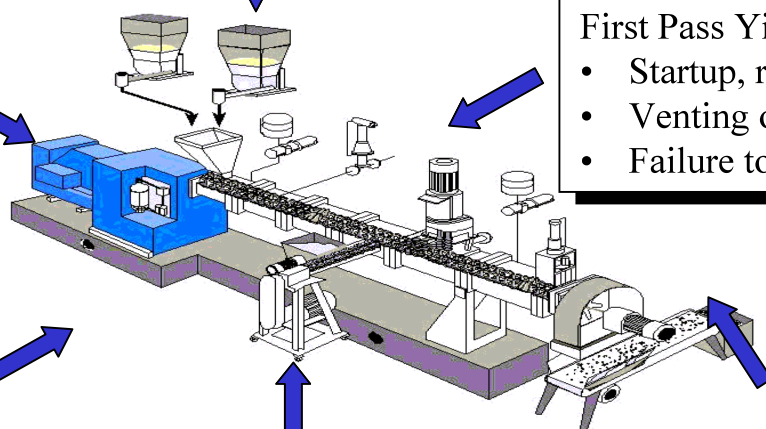
Intelligent Extruder - Benefits

% Rework Material

Raw Material Cost ($ / lb)

Energy used per pound to compound virgin material (kWh / lb)

First Pass Yield accounting for losses due to:
- Startup, resin change over, purging
- Venting of gasses
- Failure to meet customer CTQs



Energy used per pound to compound rework material (kWh / lb)

Energy Cost ($ / kWh)

Total pounds produced in a year

$ Benefits per percentage point improvement in FPY

Energy usage includes:
- Drives/motor for extruder, pelletizer
- Vacuum vents
- Feeders
- Barrel heaters
- Pumps

Potential benefits to improvement…

Direct (GE Plastics Noryl Example - 1998)
- ***Rework: Off spec costs ($350k/yr at 96% FPY)***
- ***First Pass Yield: 3% improvement saves >$20MM / yr***

Indirect
- ***Reduced energy usage per lb of product***
- ***Reduced customer returns impact future orders***
- ***Reduced load on QA lab for offline analysis***
- ***Reduced Span in JIT make to order***

What's new since 2001 OIT Review in New Orleans

- Simplified physics-based modeling of compounding process
  - greatly simplifies parameterization of models used for diagnostics and control (fewer parameters, less on-line experiments)
- On-line identification of parameters in model
  - updated model & parameters used in estimation, diagnostics and control
- On-line estimation and feedback control system for viscosity
  - track and accommodate changes in raw materials and setpoint (grade)
- Reduced off-line rheology lab testing
  - testing for calibration once per grade/family instead of once per batch!
- Can identify and distinguish small feeder drift errors from raw material property shift for use in process upset correction
- Tested integrated diagnostics and adaptive estimation and controls on lab extruder
- Optimism for scaling to industrial production rates based on use of physics-based model

All technical objectives from original proposal have been achieved and demonstrated in the lab

Sources of Finishing Variability

Process Faults

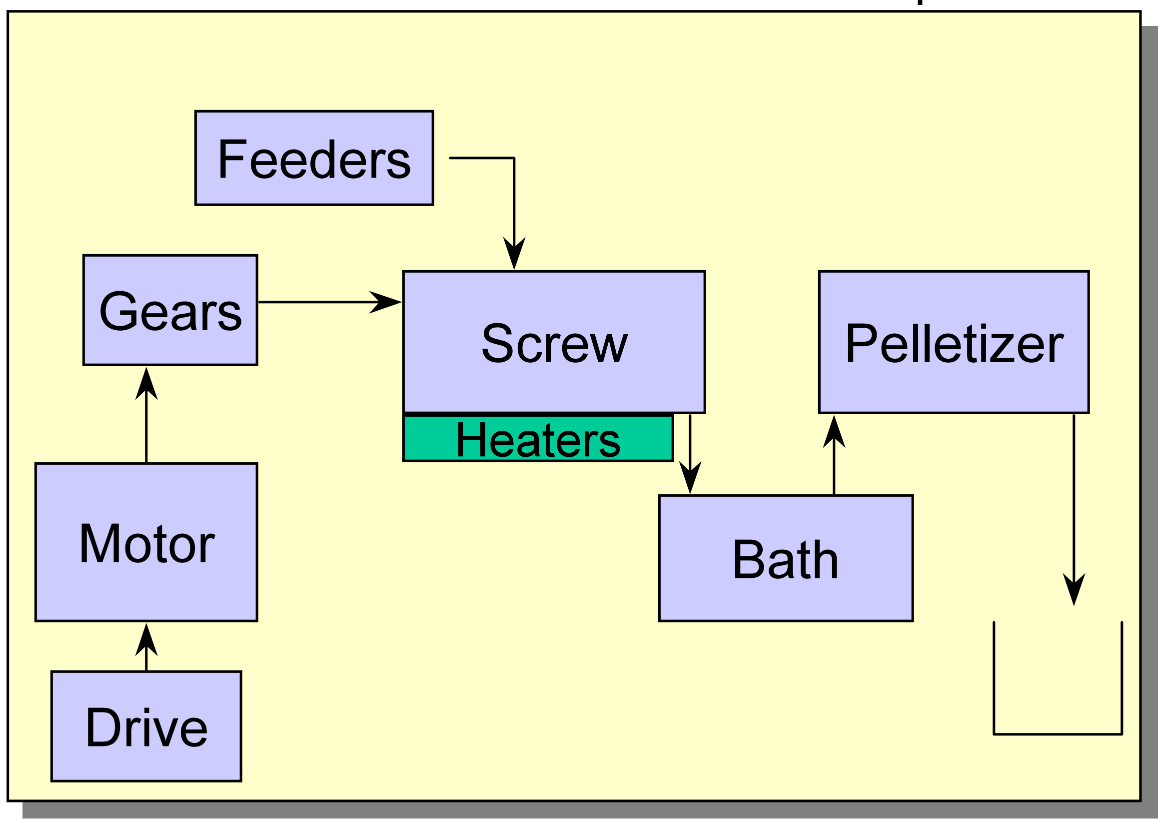
- clogged feeders, die screen
- poor barrel temp regulation
- vent, die port blockage
- strand drop, fuse
- pellets hot

Operator Errors

- formulation
- setup
- QC errors

Incoming Material Variation

- Resin MW
- Resin color
- Resin morphology
- SPD pellet
- Additive feed rates



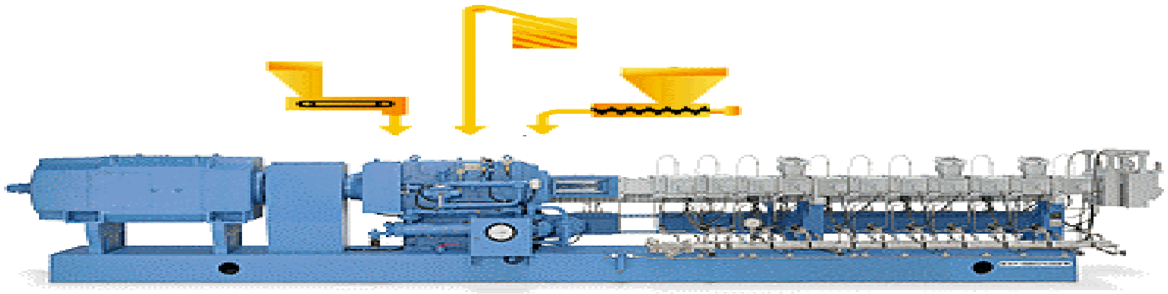
Product Variability

- MV
- Composition
- Color
- FPY
- COST / #

Equipment Faults

- feeder drive, motor , control
- dull pellet cutter
- screw shaft breakage
- screw wear
- gear box (bearing, gears)

Model-Based Approach for Estimation & Diagnostics



Online measurements

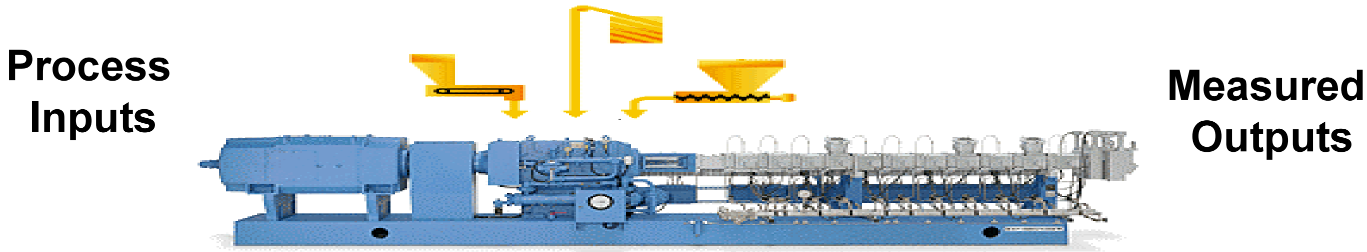
Physics-based dynamic model
- capture "nominal" input-output relation
- generic model structure applicable to wide range of product grades / operating conditions
- physically meaningful parameters
  - useful in fault detection/isolation

... the new model structure is key to simplifying the number of experiments and calibration runs in setting up the system

On-line estimation of product quality & process monitoring / diagnostics

- **continuous online estimation of product viscosity**
- **detect anomalous operation and identify root cause through model-based analysis of online measurements**

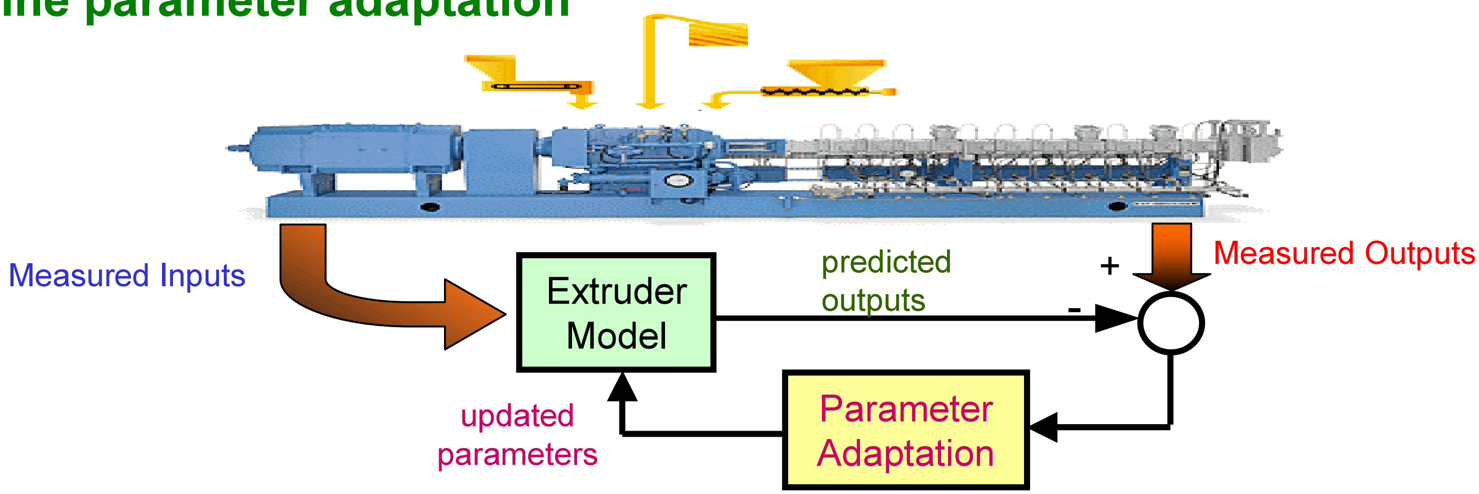
Dynamic Model for Extruder



Extruder model - capture "dynamic" relationship between inputs & outputs

- physics-based generic state-space model structure
- unknown / varying model parameters – affected by operating conditions

Use on-line parameter adaptation

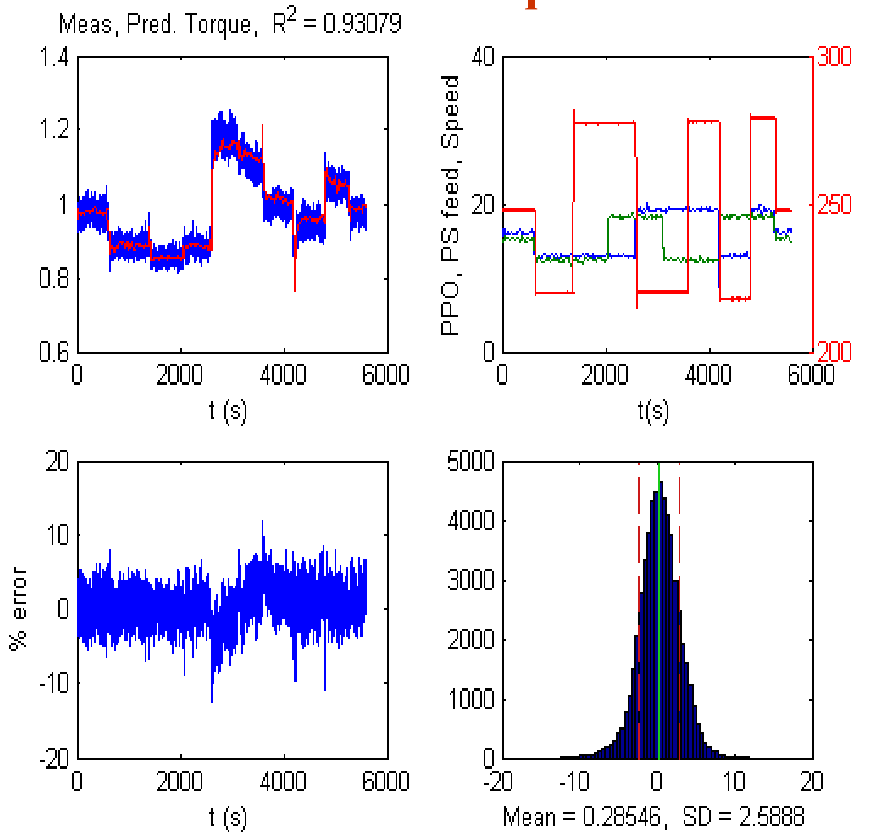


- continuously updated model with respect to changing operating conditions
- updated parameters will allow on-line estimation and diagnostics
  - exploit physical significance of model parameters

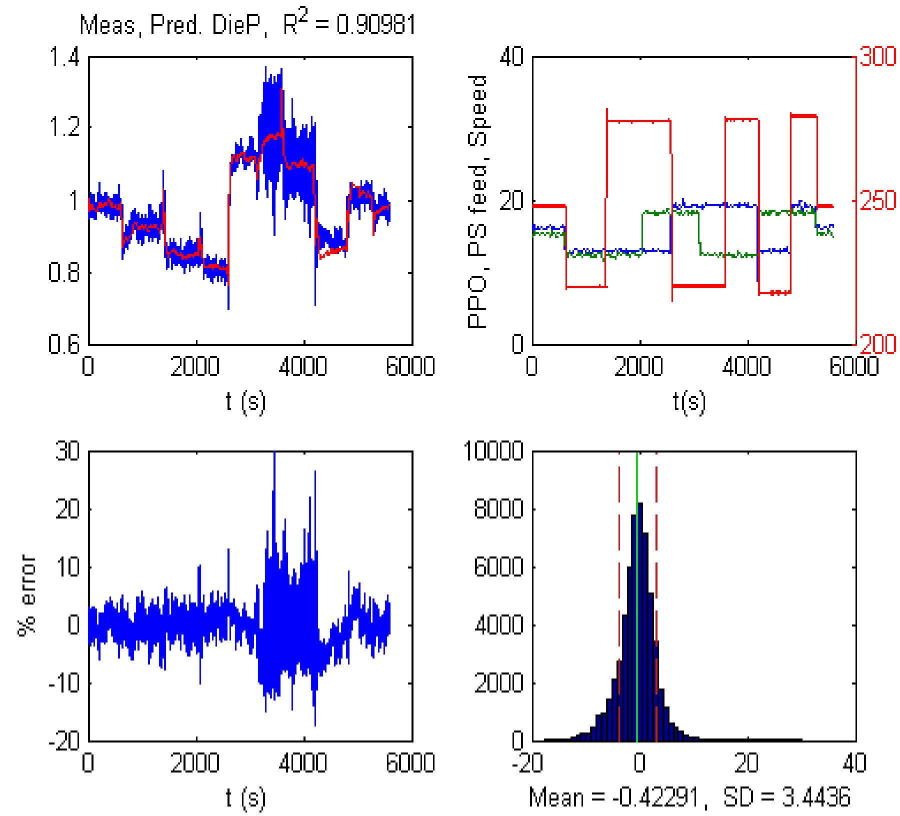
Model Fit for Torque & Die Pressure

- Data from experiment run on ZSK25 at CRD (5/08/01)
- Nominal raw materials (PPO, PS), Nominal PPO:PS ratio (x ~ 0.52)
- Model parameters fit to match measured torque, die pressure data

Torque



Die Pressure



Dynamic model predicts torque & die pressure transients very well

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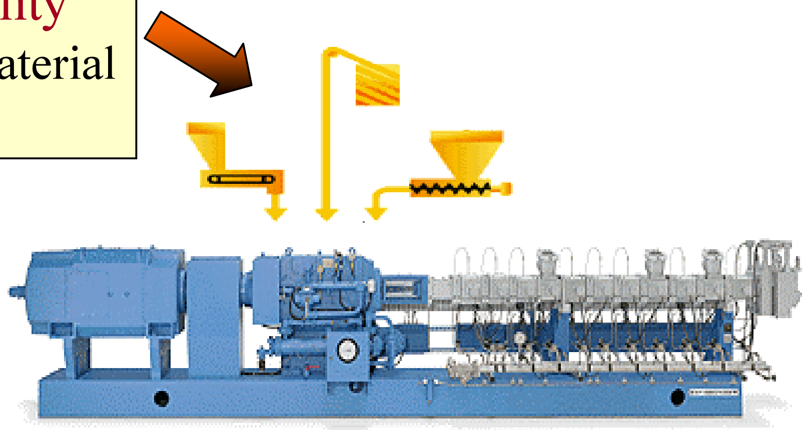
On-Line Inferential Viscosity Estimation

Why viscosity?

- key quality parameter for broad range of customers
- main cause of off-spec products (affected by raw material/composition variation)

Variability
- raw material
- feeder



Pellets

... reducing the number of experiments in the QA lab is central to practicality of this method

Off-Line Measurement of Viscosity in QA Lab
- initial calibration for each material grade/family

Initial Calibration

Measured Inputs

Measured Outputs

Viscosity Estimation from Machine Variables
- continuous, on-line

On-Line Viscosity Estimation

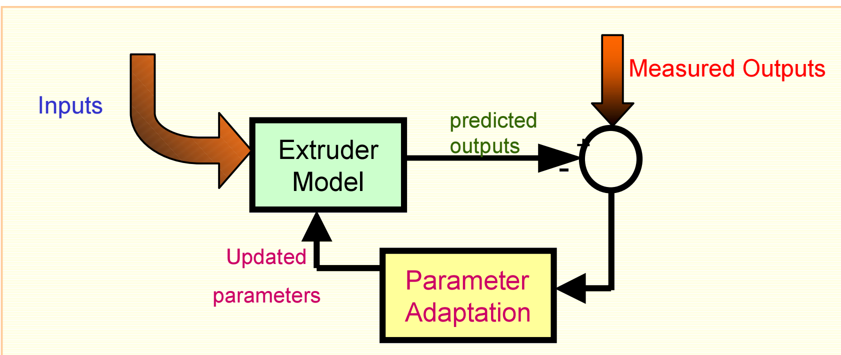
Variability in feed composition / raw material

(unknown)

Variation in Measured Outputs

variation in viscosity

updated estimate of viscosity



Model adaptation

Updated model parameters
(related to viscosity)

… the key idea here is to explicitly track the slow variations in material property using on-line measurements to keep predictor models up to date over time…without going back to the QA lab!

Model adaptation allows continuous estimation of viscosity even under unknown variations in raw material & composition

GE CR&D ZSK-25MM Twin Screw Extruder Facility

- Capable of 1200 rpm, 164 Nm of torque, resulting in throughputs of 100 lb/hr
- Computer controlled side feeders
- Utilize K-Tron loss of weight feeders
- 30HP GE Innovation Drive

... we found that models based on this 50 lb/hr lab extruder preserved the same structure when scaled up, even though parameter <u>values</u> would be quite different

Data Acquisition Capabilities

- Monitor 24 data channels simultaneously
- Monitor barrel temperatures, barrel heater reactions, feed rates, torque, speed, die pressure, melt temperature
- Motor shaft encoder

Procedure

- Run experiments with Noryl PX5511 (PPO+PS) at different conditions
- Collect pellet samples at steady state conditions and measure viscosity in lab (off-line)
- Compare viscosity estimated using on-line measurements with off-line lab measurements

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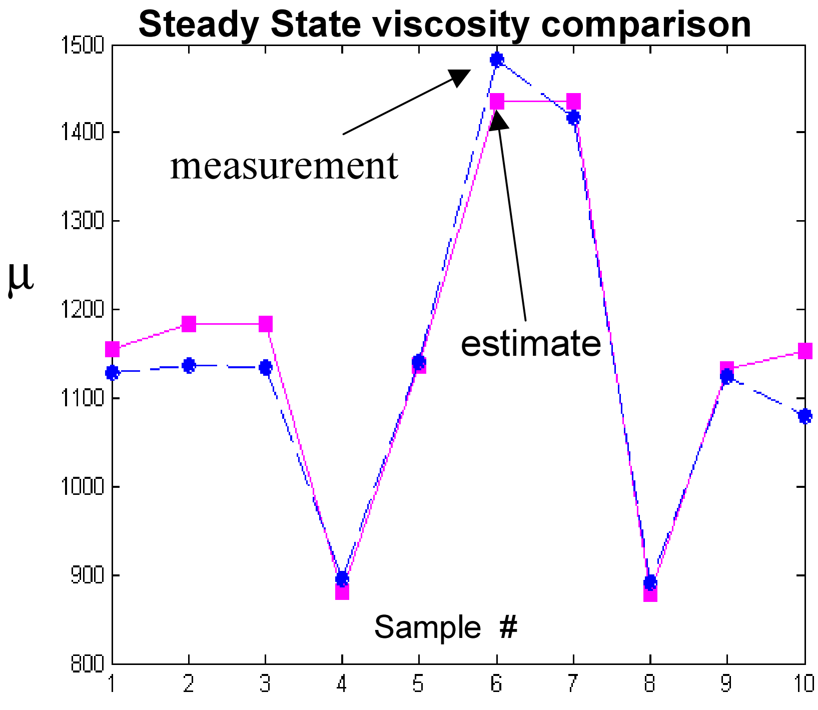
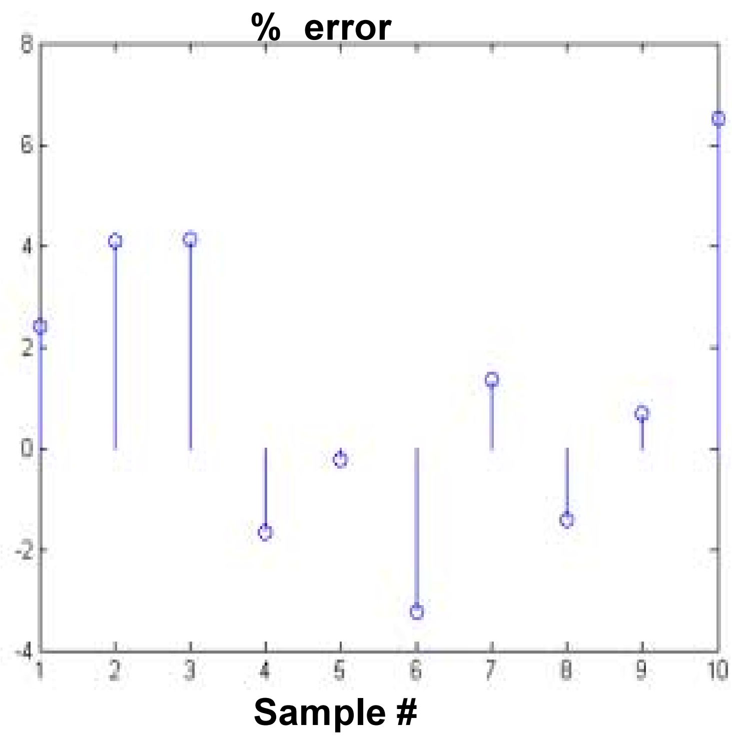
On-Line Estimation vs. Off-Line Measurement

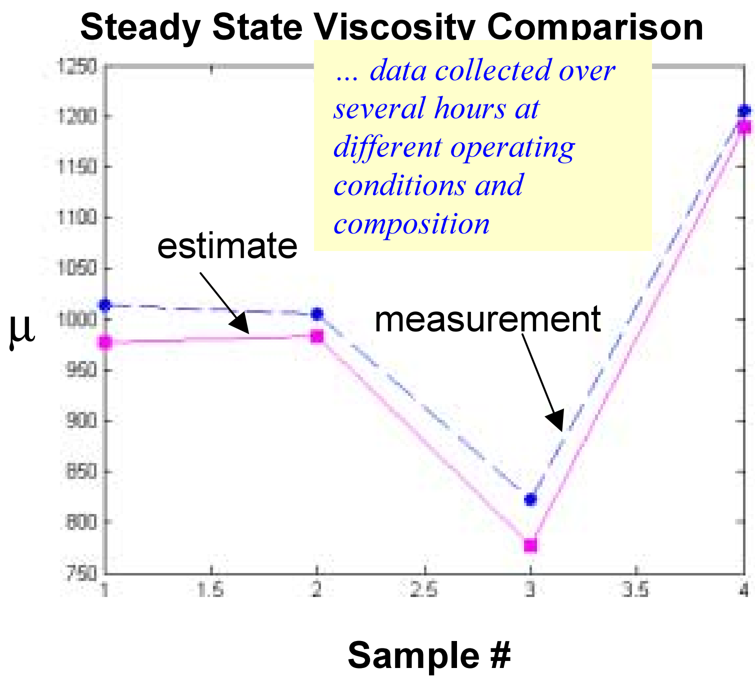
- Experiment run on ZSK25 at CRD (5/08/01)
- **Nominal raw materials (PPO, PS)**
- **Nominal PPO:PS ratio (PPO fraction x ~ 0.52)**
- Off-line measurement of viscosity from 10 samples at SS conditions
- Compare off-line measurement with on-line estimation of viscosity from adapted parameters

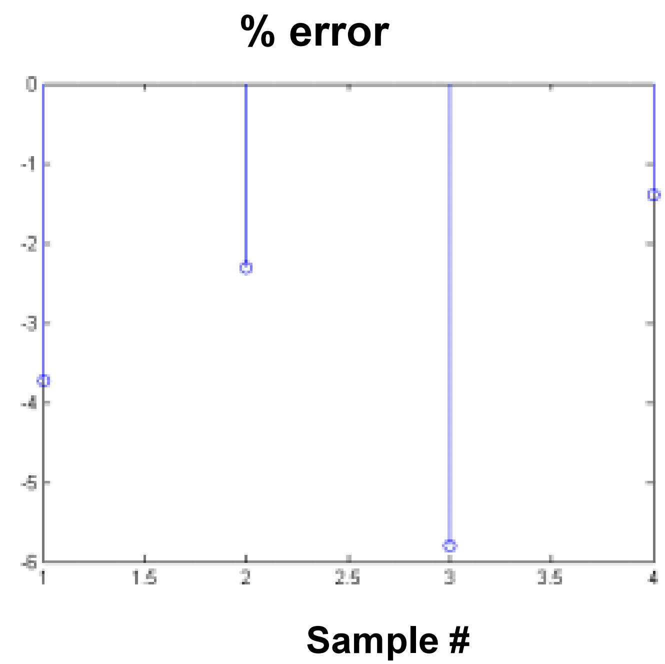




Estimation vs. Off-Line Measurement - Change in Raw Material

- Experiment run on ZSK25 at CR&D (10/11/01)
- **Change in raw material - medium IV PPO (mixture of .46 & .33 IV PPO)**
- **Nominal PPO:PS ratio (PPO fraction x ~ 0.52)**
- Off-line measurement of viscosity from 4 samples at SS conditions
- Compare off-line measurement with on-line estimate from adapted parameters





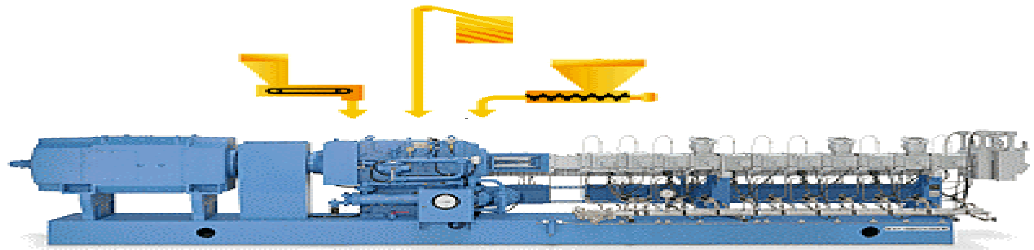
Online viscosity estimation matches well with off-line measurement

- parameter adaptation captures effect of raw material change

Model-Based Diagnostics - Approach

Unknown Variability

- raw material
- feeder bias



Inputs

Extruder Model

predicted outputs

Measured Outputs

+

-

updated parameters

Parameter Adaptation

Perform adaptation when detect model mismatch

Updated model parameter estimates

Detection Algorithm

- match parameter change with fault signature

Identify source of variability

- assume one fault at a time

raw material variation

Nominal

feeder variation

Fault Signatures

- distinct parameter change (from nominal) for anomalous operation
- physics based - generically applicable

Results for Viscosity Estimation & Diagnostics

Goal: Test viscosity prediction stability and fault diagnosis with various anomalies

No fault conditions

Fault Conditions

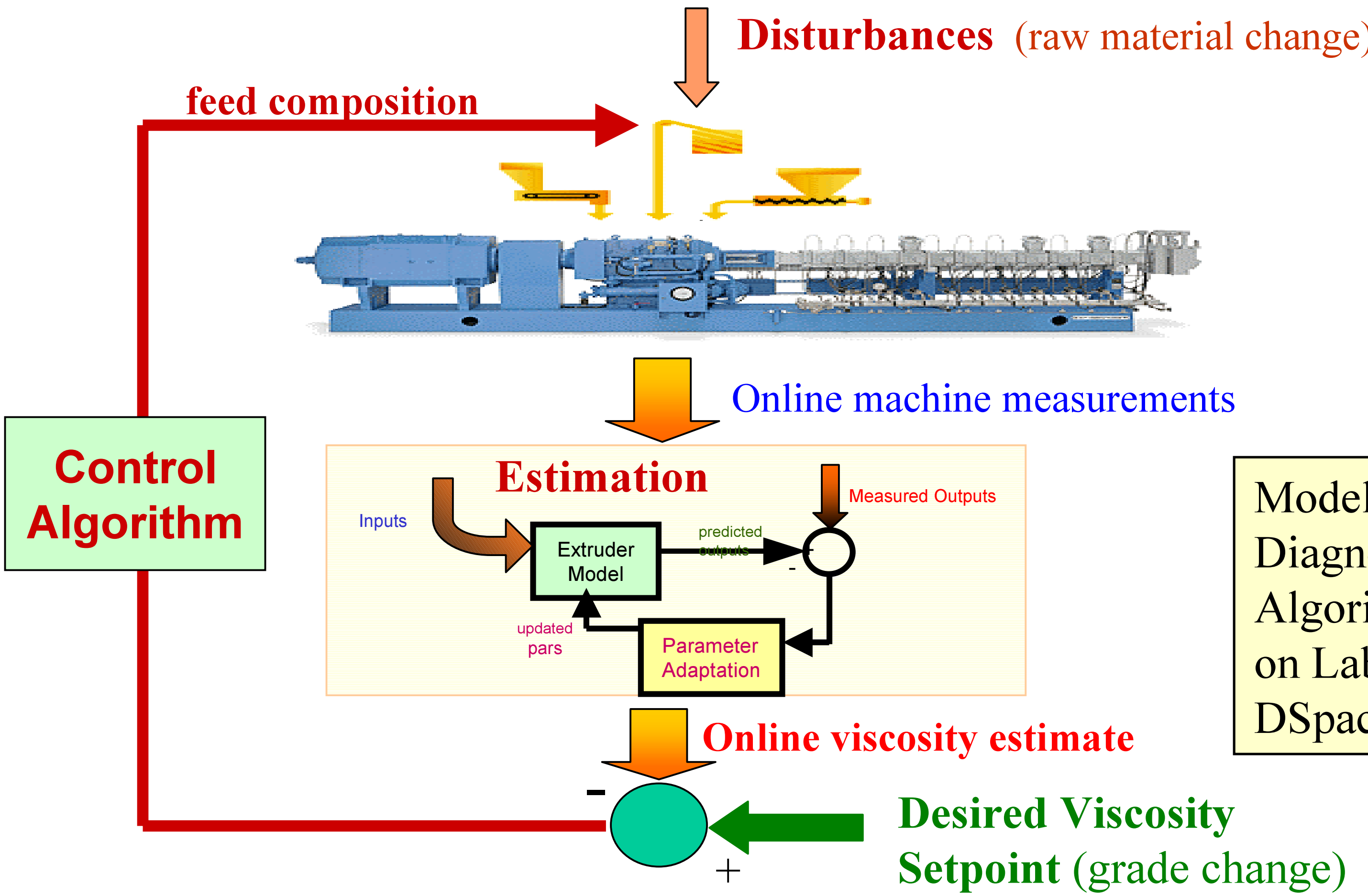
Date of Expt	Actual Expt. Conditions	Diagnostics Result	Estimated vs. measured viscosity (μ)	Estimated slope (μ_1)
06/25/01	Nominal raw material Calibration run	Nominal	1139 (1152)	2944
05/08/01	Nominal raw material	Nominal	1174 (1129)	2891
05/22/01	Nominal raw material	Nominal	1167 (-)	3083
07/25/01	Nominal raw material	Nominal	1155 (1196)	2843.5
08/27/01	Low IV PPO	Lower IV PPO	877 (920)	2537
10/11/01	Med IV PPO	Lower IV PPO	1002 (1010)	2550
11/14/01	Med IV PPO	Lower IV PPO	940 (964)	2647
12/04/01	Med IV PPO	Feeder Bias *	930 (995)	2920
12/06/01	Med IV PPO	Lower IV PPO	968 (980)	2594
12/14/01	Med IV PPO + unknown feeder bias*	Multiple Faults	1095 (1099) 1135**	2554 2516**

* Detect a fault but misclassify source due to multiple simultaneous faults (but estimate viscosity OK)

** Estimated after feeder bias correction

Feedback control using on-line viscosity estimate

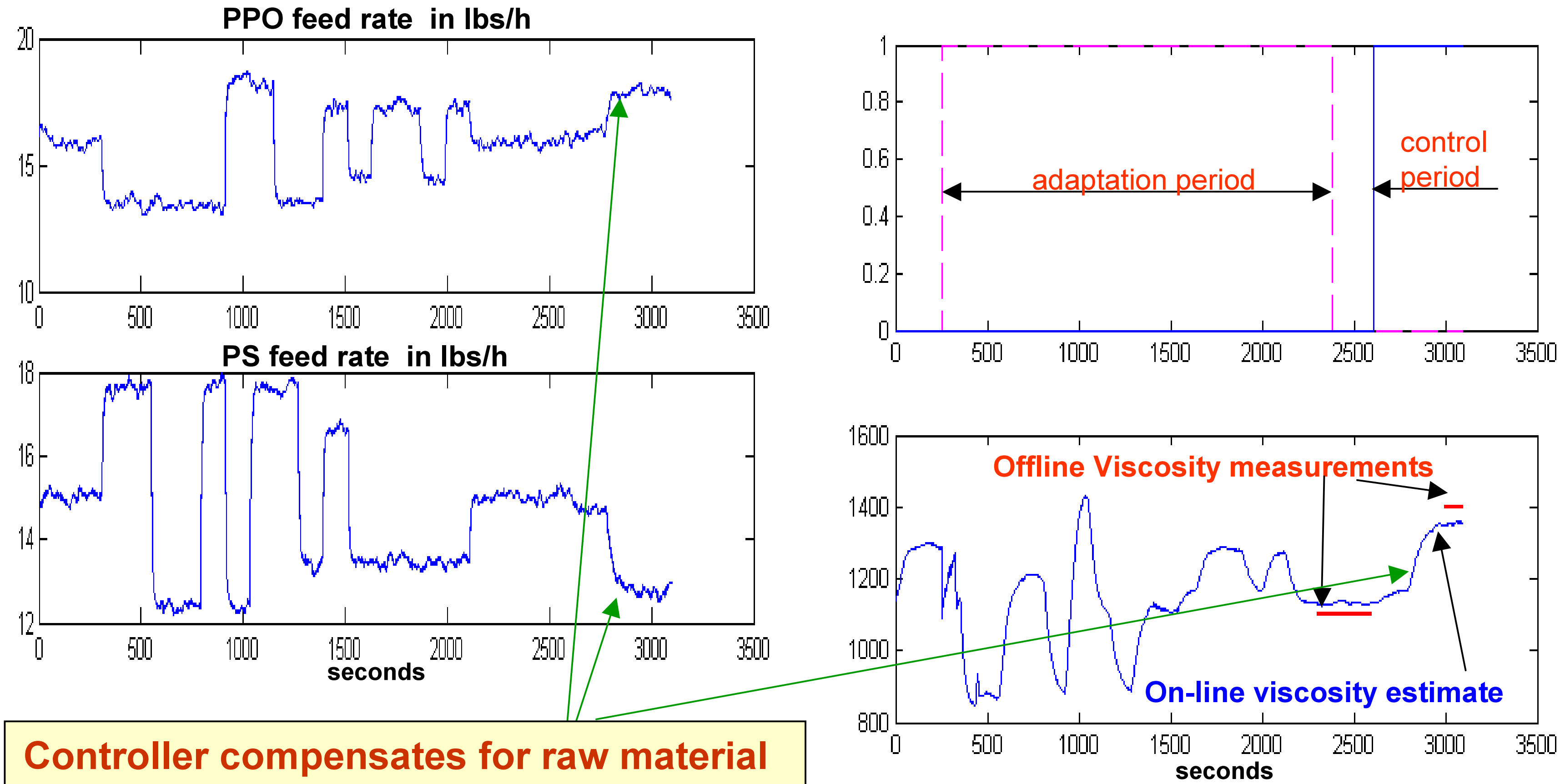
- manipulate feed composition as control input
- track changing viscosity setpoint (grade transition)
- reject effect of unknown disturbances (raw material variation)



Model-based Estimation, Diagnostics & Control Algorithm Implemented on Lab Extruder using DSpace

Expt Demo of On-Line Viscosity Estimation & Closed-Loop Control

- Experiment run on ZSK25 at CRD (12/14/01)
- **Change in raw material (med. IV PPO), High PPO fraction** (x ~ 0.57)
- Adapt model parameters & update viscosity estimate
- Reject effect of raw material change (disturbance)



Controller compensates for raw material change (lower IV PPO) by changing feed ratio to get viscosity on target

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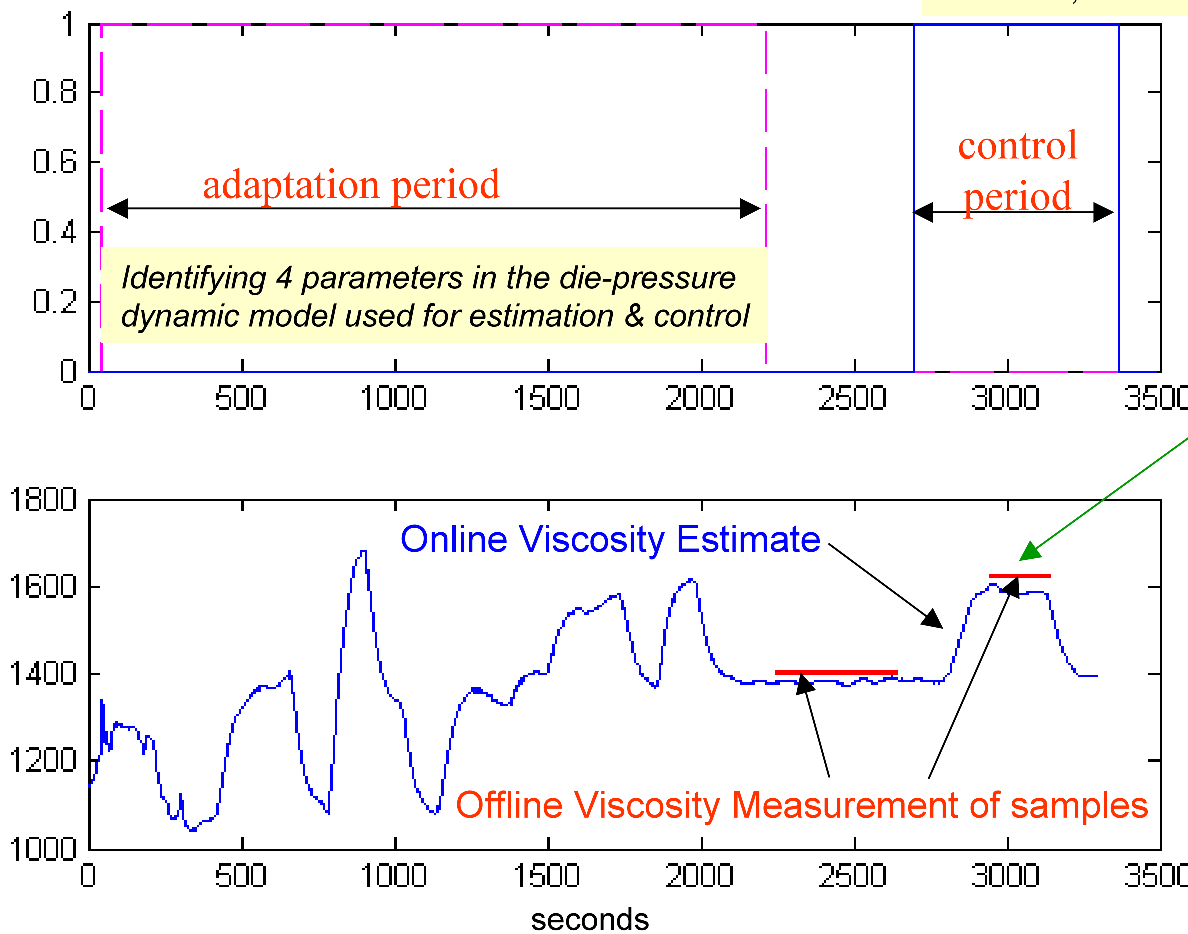
Expt Demo of On-Line Viscosity Estimation & Closed-Loop Control

- Experiment run for calibration on ZSK25 at CRD (12/14/01)
- **Nominal raw materials,** **High PPO fraction** (ratio ~ 0.57)
- Adapt model parameters & update viscosity estimate
- Track viscosity setpoint change

Switch off the identification and turn on closed loop controller, then change the setpoint (grade change)



Achieve on-line grade change without recalibration!

Controller tracks change in viscosity setpoint

Enables on the fly grade change campaigns!

Your team and ours working remotely to achieve plant productivity

GE's OnSite Support ^{SM} Center

(800) 533-5885

Staffed 24 hours/day & 7days/week

Intelligent Extruder Summary

- Simplified physics-based modeling of compounding process
  - greatly simplifies parameterization of models used for diagnostics and control (fewer parameters, less on-line experiments)
- On-line identification of parameters in model
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- Can identify and distinguish small feeder drift errors from raw material property shift for use in process upset correction
- Tested integrated diagnostics, adaptive estimation and controls on lab extruder
- Optimism for scaling to industrial production rates based on use of physics-based model
- Plan for scale-up at GEP, WP, commercialization with GEIS

More Information
(see handout)
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